

# **PATTERNS OF BRITTLE DEFORMATION UNDER EXTENSION ON VENUS; G.A.**

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The development of fractures at regular length scales is a widespread feature of Venusian tectonics. Models of lithospheric deformation under extension based on non-Newtonian viscous flow and brittle-plastic flow [1,2] develop localized failure at preferred wavelengths that depend on lithospheric thickness and stratification. The characteristic wavelengths seen in rift zones and tessera can therefore provide constraints on crustal and thermal structure [3]. Analytic solutions were obtained by [4] for growth rates of infinitesimal perturbations imposed on a one-dimensional, layered rheology. Brittle layers were approximated by perfectly-plastic, uniform strength, overlying ductile layers exhibiting thermally-activated power-law creep. This study investigates the formation of faults under finite amounts of extension, employing a finite-element approach. Our model incorporates non-linear viscous rheology and a Coulomb failure envelope in the manner of [5]. An initial perturbation in crustal thickness gives rise to necking instabilities. A small amount of velocity weakening [cf. 6] serves to localize deformation into planar regions of high strain rate. Such planes are analogous to normal faults seen in terrestrial rift zones. These "faults" evolve to low angle under finite extension [cf. 7]. Fault spacing, orientation and location, and the depth to the brittle-ductile transition, depend in a complex way on lateral variations in crustal thickness. In general, we find that multiple wavelengths of deformation can arise from the interaction of crustal and mantle lithosphere.

To calculate patterns of deformation, we use a finite element (FE) program for incompressible Newtonian viscous fluid flow via the penalty method [8], modified to treat non-Newtonian flow problems [9,10]. Gravitational body loads are applied to individual elements. An initial viscosity is calculated for a state of uniform extension using the power-law relation

$$\mu_{\text{eff}} = B \epsilon_{\text{max}}^{(1-n)/n} \exp(Q/nRT), \quad (1)$$

where  $\epsilon_{\text{max}}$  is the maximum principal shear strain rate,  $n$  is the power-law exponent,  $R$  is the gas constant,  $T$  is temperature,  $Q$  is the material activation energy, and  $B$  is a material strength constant. An iterative procedure re-calculates the effective Newtonian viscosity  $\mu(i,j)$  for each quadrilateral FE. The maximum viscosity is limited to that allowed by the Coulomb failure criterion. Before proceeding with any time-steps, we iteratively calculate the deviatoric strain rate at zero strain resulting from the brittle-plastic and velocity-weakening effects. Strain rates are locally enhanced in elements with ductile strength less than that of mantle at the base of thickened crust. Higher strain rates imply reduced effective viscosity of these elements. Strain is preferentially accommodated where viscosity is lower, leading to further reduction in strength. This feedback eventually results in highly localized rates of deformation, i.e., the material breaks and undergoes faulting. Localization of deformation is the result of non-linear dynamics and is somewhat unstable with respect to initial conditions. Generally more than 100 iterations are required to reach steady state, even with over-relaxation on strain rate. Finite deformation is then calculated by a second-order time-step integration, with dynamic topography developing at the free surface.

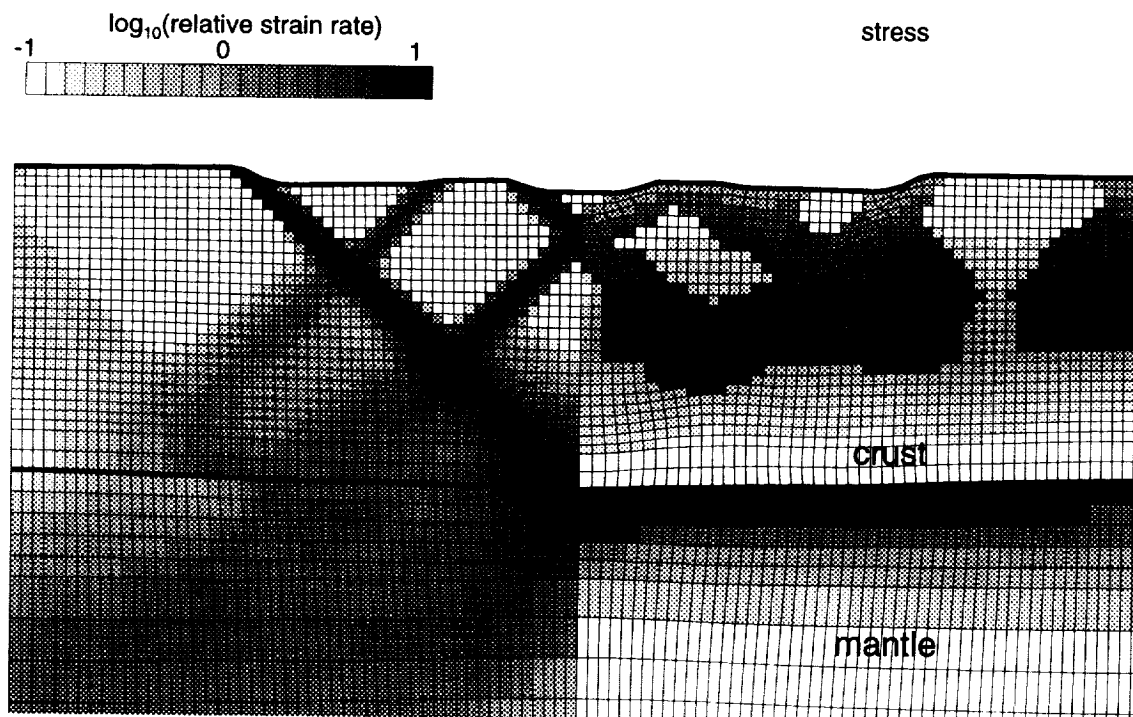
For the crust we use a recent experimentally obtained flow law for the rheology of diabase [11] under extremely dry conditions representative of the surface of Venus, with  $n=4.3$  and  $Q=482$  kJ/mol in equation (1). The stronger olivine rheology preferred by [5] is assumed for the mantle, with  $n=3$  and  $Q=540$  kJ/mol. The brittle-ductile transition thereby occurs at about 8-10 km in the crust and 15-20 km in the mantle. We employ a lithospheric thermal model as discussed in [3], with a surface temperature gradient of 25 °K/km. The initial strain rate is  $\epsilon_0 = 10^{-14}$  s<sup>-1</sup>. A brittle strength envelope provides an upper bound to viscosity at a given depth and strain rate, such that deviatoric stress  $\tau_{\text{max}} \leq \sigma_0 + C \rho g z$ . The Coulomb strength coefficient  $C$  is velocity-weakening, depending on strain rate as  $C=C_0 - 0.05 \log_{10}(\epsilon/\epsilon_0)$ , with  $0.25 < C < 0.4$ ,  $C_0 = 0.36$  and  $\sigma_0 = 1$  MPa. This value of  $C_0$  corresponds to an internal friction coefficient of about 0.71. A perturbation of crustal thickness between  $\pm 1$  and  $\pm 10\%$ , at a 50 to 100 km wavelength, is introduced.

For a range of crustal thicknesses of 8 to 18 km, preliminary results show that faulting develops at multiple scales when brittle-ductile transitions occur in both the crust and upper mantle, with the width of the shortest wavelength features being about twice the thickness of the brittle crust. Longer wavelength features occur at twice the depth to the base of the upper mantle lithosphere. The model boundary undergoes a prescribed rate of uniform extension. Integration of strain rate over time to overall strains of 10% produces conjugate patterns of faulting and rifting. Larger amounts of strain generally exceed the range of applicability of quadrilateral FE's.

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The pattern of normal faults and sloping terraces (Figure 1) indicates a fairly realistic simulation of the behavior of layered brittle-ductile rheology. Localized faulting develops when the initial perturbation wavelength is less than about 8 times the total thickness of the lithosphere (base of brittle mantle). Longer wavelength perturbations produce stable extension of the crust, and brittle-plastic necking of the mantle lithosphere. Perturbations at wavelengths of less than twice lithospheric thickness produce a single pair of conjugate normal faults meeting at the base of the crustal lithosphere. The growth of fault-like zones indicates a mechanism for the development of linear features at multiple scales due to extension in a Venus lithosphere with a variable-thickness crust. We plan to use this model to investigate the relationship between deformation patterns, wavelength of perturbation, and strength envelopes.

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**Figure 1.** Finite element model with assumed flow laws and thermal structure. Original crustal structure is 50 km wide, 15 km deep, with  $\pm 5\%$  variation in crustal thickness, greatest at the center. Density of crust is  $2900 \text{ kg/m}^3$  and mantle is  $3300 \text{ kg/m}^3$ . The center of the grid is a symmetry axis, with periodic boundary conditions on the sides. The bottom boundary at 50 km depth has no vertical displacement, and is shear-stress free. The grid shown has undergone a total extension of 6%. Regions of high strain rate are shown on the left by the darkly shaded regions. Regions on the right are shaded where the Coulomb brittle failure envelope is locally exceeded. Dynamically produced topography at the surface reflects the perturbation wavelength as well as finer scales of faulting generated by the interaction of crustal and mantle lithosphere.